Materials used in drinking water distribution systems: contribution to taste-and-odor

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Abstract In order to assist drinking water utilities with identifying the possible sources and causes of taste-and-odor conditions associated with materials used in distribution systems, we evaluated information from case studies and a database from the National Sanitation Foundation (NSF), International. This database identified chemicals that had leached from drinking water system components during testing of materials under ANSI/NSF Standard 61, which provides information to water utilities on potential taste-and-odor and health concerns from the use of new materials. The data were arranged to provide a process for locating the potential source of a taste-and-odor event. After a sensory analysis is conducted on the drinking water samples, the descriptor can be matched with categories on the "Drinking Water Taste and Odor Wheel 2000" in order to suggest the candidate material.

Keywords System materials; taste-and-odor

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Introduction

A water utility needs to provide drinking water free of objectionable tastes and odors since users often judge the quality of the water at their tap mainly by its aesthetic properties such as color, taste, and odor. Addressing all sources of taste-and-odor problems is critical for maintaining public confidence in the drinking water supplied. This paper focuses on system materials as potential sources of taste-and-odor conditions.

Common materials used in drinking water storage and distribution systems include (Burlingame and Anselme, 1995):

- Pipes and mains: cast iron, ductile iron, steel, reinforced concrete, asbestos cement; thermoplastics, including polyvinyl chloride (PVC), chlorinated polyvinyl chloride (CPVC), high density polyethylene (HDPE), polybutadiene; composites such as glass fiber reinforced plastic (GRP) using thermoplastic epoxy or polyester resins
- Home plumbing: copper, lead, galvanized steel, and thermoplastics
- Tanks and reservoirs: cementitious products with organic additives
- Ancillary equipment and its coating, joining, and sealing materials: gaskets, o-rings, fittings, valves, packing, site-applied products, sealants, lubricants, paints, primers, additives, adhesives, solder
- Linings and coatings: epoxy, polyester, polyurethane, and polyacrylate resins; cement mortar, bituminous materials
- Sealing systems: rubbers, including ethylene–propylene terpolymer (EPDM), styrene–butadiene rubber (SBR), nitrile–butadiene rubber (NBR), silicones, polybutenes

Organic polymeric materials are potentially capable of leaching monomers, low molecular weight polymer units, and additives such as plasticizers, antioxidants, and application solvents; some of these may impart tastes and odors to the system water. Chemicals can enter the water from leaching of additives or coatings used in the system material, leaching of original material itself, reaction of materials with chlorine or other direct additives, as

well as biotransformation of leachates by fungi, algae, or bacteria in the system. However, the sources of chemicals may be subtle or unanticipated. As found in the case studies, unusual chemical contamination may arise from certain conditions related to the surface application of coatings and adhesives, or from non-compliance issues (e.g. addition of solvents or other chemicals not in the approved formulation) (Rigal, 2001). Often, adverse taste-and-odor conditions occur after a new installation or following maintenance, and the offending chemical dissipates with time as the system is flushed. Of course, periods of stagnation also contribute to increased concentrations of trace level chemicals in the stagnant water.

Organoleptic testing of potential system materials is a first step in the European approval process, followed by cytotoxicity testing and analytical screening; most of the material rejections occur during organoleptic testing. Sometimes chemical leaching results in very low levels of chemicals, below the allowable health effects limits, yet an objectionable odor may still be imparted.

ANSI/NSF Standards 60 and 61 are used in the USA to establish minimum health effects requirements for a broad range of materials and components utilized in drinking water systems. Standard 60 covers direct chemical additives and Standard 61 covers chemical contaminants and impurities indirectly imparted to drinking water by components, and materials. Prior to testing for taste-and-odor or for health effects manufacturers and suppliers must provide a "positive list" of known chemicals associated with each material of product to be tested.

In Europe, "positive lists" are lists of substances that have been evaluated as acceptable, generally in terms of toxicity. The positive lists can be useful for contemplating potential sources of tastes and odors, although the chemicals listed do not necessarily impart odors to drinking water coming into contact with these materials. Europeans have over 50 permitted lists of additives, monomers, and structural or mechanical types of materials. In France, the Centre de Recherche et Controle des Eaux, Ville de Paris has developed a standard method for the sensory evaluation of materials intended for contact with drinking water (Rigal, 1992, 1995).

A positive list system is not used in the United States, where standards are either performance-based (such as AWWA standards), or health-effects-based (such as ANSI/NSF Standard 61). While there are no aesthetics-based standards in the USA, manufacturers must disclose what ingredients and materials are used in their products prior to the NSF-certification process.

Methods and results

In our literature review and analysis, case studies were identified in which chemicals leaching from drinking water distribution system materials affected the organoleptic quality of the drinking water. Details can be found in a report by American Water Works Association Research Foundation (2003), in which materials and chemicals that imparted tastes and odors to drinking water are identified. The exhaustive list of chemicals found by NSF to leach from system components is provided below.

Pipes and liners

Cement/concrete. 2,4,6-tribromoanisole; 2,4,6-tribromophenol (Bromol); 2,4,6-trichloroanisole (Tyrene); 2,4,6-trichlorophenol; antimony; calcium carbonate (lime); calcium sulfate; chromium; diethanolamine; diethylene glycol; dioxin (TCDD); cipropylene glycol; dipropylene glycol-*t*-butyl ether; furan; iron oxide; magnesium oxide; melamine-sulfonate; naphthalene-sulfonate; *o*-phenylphenol; phenoxypropanol; tetracalcium trialuminumosulfate; tetraethyl diphosphate; triethanolamine; vanillin.

PVC/CPVC. 1,3-butadiene; antimony; calcium carbonate; calcium stearate; carbon black; chlorophenol; cyclohexanone; dibutyltin; diethylhexylphthalate; disononyl phthalate; ethyl acrylate; formaldehyde; monobutyltin; paraffin wax; polyethylene wax; titanium dioxide; tributyltin; vinyl chloride monomer.

Polyethylene, HDPE, PEX. Acetophenone; 2,4-bis (dimethylethyl)phenol; benzene; benzothiazole; bis-(dimethylethyl)benzene; bisphenol A; BHT (methyl di(t-butyl)phenol); carbon disulfide; cyclohexadienedione; cyclo-hexanone; cyclopentanone; diazadiketo-cyclo-tetradecane; dicyclopentylone; dimethylhexanediol; di-*t*-butyl oxaspirodecadiene-dione; hydroxymethylethylphenyl ethanone; isobutylene; methanol; methyl butenal; methyl di-*t*-butyl hydroxyphenyl proprionate; methyl (di-*t*-butylhydroxy-phenyl)propionate; methylbutenol; nonylcyclopropane; phenolics; phenylenebis-ethanone; propenyl-oxymethyl oxirane; *t*-butanol; tetrahydrofuran; trichloroethylene.

Polyurethane coatings and liners. 1,4-butanediol; 4,4-methylenedianiline; bis(2-ethyl-hexyl)phthalate; bisphenol A diglycidyl ether; butyl benzyl phthalate; diphenyl(ethyl)phosphine oxide; di-*t*-butyl methoxyphenol; ethylhexanol; tetramethyl piperidinone; toluene diamine.

Epoxy coatings and liners. 1,1-dichloroethene; 1-methoxy-2-propanol; 4,4′-methylenedi-aniline; benzaldehyde; benzidine; benzyl alcohol; bisphenol A; bisphenol A diglycidyl ether; bisphenol F; butoxyethanol; diethylenetriamine; diphenyl ether; epichlorohydrin; ethyl benzene; ethylhexanol; isobutyl acetate; isopropoxy propanol; methylisobutyl ketone; *n*-butanol; *n*-butyl acetate; nonylphenol; phenol; toluene; tripropylene glycol; styrene.

Joining and sealing materials (adhesives, caulk, flux)

Diethyl phthalate; ethanolamine; lead; methacrylic acid; organotins.

Gaskets and O-rings

Nitrile-butadiene rubber. 1-phenylethanone; 2-(2-butoxyethoxy)ethanol; 2,4,5-trichlorophenol; 2-ethyl hexanol 2-phenyl-2-propanol; acrylonitrile; benzothiazole; benzothiazolethione; benzothiazolytiomorpholine; bis-(ethylbenzyl) ester; butadiene; butoxyethoxy ethanol; carbon disulfide; cyclooctadiene; dicyclohexyl urea; dimethyl carbamic chloride; dimethyl cyclohexyl urea; dimethyl dithiocarbamate propionitrile; dimethylethyl phenol; diphenyl guanidine; isocyanatocyclohexane; isothiocyanatoethane; mercapto-benzothiazole; methoxybenzene; tetramethylthiourea; tetramethylurea; tri(butoxyethyl) phosphate; tripropenyl triazinetrione.

Styrene butadiene rubber. 1,2-dichloropropane; 2,4,5-trichlorophenol; acetophenone; alpha-methylstyrene; benzothiazole; dimethyl benzene methanol; diphenyl guanidine; di-*t*-butylhydroxy-methyl cyclohexadienone; methylene chloride; methyl octanoate; phenyl-benzenediamine; 1-phenylethanol; phenylethylphenol isomers; styrene; tetrabutyl urea; trimethyl quinoline.

Lubricants (grease, silicones, primers, sealants).

3-chloro-1,2-propanediol; cyclohexanone; *p*(*t*-butyl)phenyl glycidyl ether; silicones.

Solder

Copper; antimony.

Thread compound

Benzaldehyde; diacetone alcohol; ethoxylated bisphenol A dimethacrylate; lead; methacrylic acid; methanol; phenolics; tetrachoroethane; tetramethylene glycol dimethacrylate.

Taste, odor and toxicological characteristics of leached chemicals

The starting point for our review was the above lists of chemicals found by the NSF to leach, or have the potential to leach for each material type. Leached chemicals deemed to potentially contribute to taste-and-odor (based on odor thresholds), and/or cause toxicity concern, were included in the Tables.

The first set of Tables (1–7) display sensory descriptors as well as health effects for selected leached contaminants and subsequent system reaction products, where information could be found in the literature. Unfortunately, organoleptic properties and/or health effects data for many of the compounds used in complex material formulations are not known or not generally available.

Relating taste-and odor characteristics to the drinking water taste and odor wheel 2000

A chemical migration test that includes organoleptic analysis should be used as the reliable criterion for approving a material for drinking water storage and distribution systems. Taste-and-odor information can only be obtained by sensory analysis (Rigal and Rauzy, 2001), even though it might be tempting to compare the NSF data with reported organoleptic information about individual chemicals in order to surmise potential taste-and-odor sources.

Tables 8 presents sensory information summarized in a different way so that identification of possible sources of taste-and-odor can be attempted once a descriptor is identified by sensory analysis. The descriptor categories are arranged according to the "Drinking Water Taste and Odor Wheel 2000" (Suffet *et al.*, 1999). The candidate materials are based on previously reported cases, and/or migration(leaching) studies, and does not guarantee that the cause of any particular taste or odor can be identified. Sensory analysis may be limited by the panelists' ability to describe or characterize accurately the taste or odor associated within the odor wheel category. For example, if a panel is used to detect earthy/musty odors, there may be a bias that any new odor is also described as earthy/musty, especially if near the odor threshold.

A refinement of the categories and descriptors above is given in the outline below Table 8.

Detailed descriptions of taste-and-odor wheel categories

1. Odor Wheel Category: medicinal/phenolic; may be "sweet" or "sweet phenolic"
   (a) Subdescriptor – medicinal/phenolic.
   Chemical(s): phenols are directly leached from materials. Halophenols: reaction from disinfectant (chlorine) and phenols, or reaction of chlorine and phenol in bromide and/or iodide-bearing waters.
   Sources/materials: acrylic coating in reservoir, styrene butadiene rubber, gaskets and o-rings, pipes and liners, polyethylene, HDPE, PEX, PVC pipe with primer and cement (probably not PVC itself)
   (b) Subdescriptor – sharp/sweet
   Chemical: diethylene glycol
   Sources/materials: dye solvent
2. Odor Wheel Category: chemical/hydrocarbon/miscellaneous
   (a) Subdescriptor – solvent, airplane glue, varnish, paint

Table 1 Chemicals leached from cementious pipes and liners

Chemical leached	CAS No.	Source or primary use if additive	Allowable limit or risk factor	Potential health effects	Odor (or taste) threshold	Odor (or taste)
2,4,6-Tribromoanisole	607-99-8	Biotransformed 2,4,6-tribromophenol	(no MCL)	Unknown	30 pg/L	Musty
2,4,6-Tribromophenol	118-79-6	Fungicide, bactericide	(no MCL)	Unknown	600 ng/L	Medicinal
2,4,6-Trichloroanisole	87-40-1	Biotransformed 2,4,6-trichlorophenol	(no MCL)	Unknown	30 pg/L	Musty
2,4,6-Trichlorophenol	88-06-2	Fungicide, bactericide	1.0 µg/L (NJ) 700 µg/L (ME)	Probable carcinogen (IARC B2)	> 1 mg/L	Medicinal
Diethanolamine	111-42-2	Cement grinding aid	(no MCL)	Low toxicity	0.27 mg/L	Ammonia-like
Diethylene glycol	111-46-6	Dye solvent	(no MCL)	Kidney damage		Sharp/sweet
Furan	110-00-9	Manufacturing by-product	(no MCL)	Probable carcinogen (IARC B2)		Resinous
Iron Oxide	1309-37-1	Raw material contaminant	SMCL for Fe^{+2} 0.3 mg/L	None likely	Taste 40 mg/L	Metallic
Magnesium oxide	1309-48-4	Raw material contaminant	(no MCL)	None likely		Chalky
o-Phenylphenol	90-43-7	Fungicide	(no MCL)	Prop. 65 (CA) carcinogen		Medicinal
Triethanolamine	102-71-6		(no MCL)	Possible carcinogen (IARC 3)		Ammonia

Table 2 Chemicals leached from epoxy resins

Chemical leached	CAS No.	Source or primary use if additive	Allowable limit or risk factor	Potential health effects	Odor (or taste) threshold	Odor (or taste)
Styrene	100-42-5		MCL 0.1 mg/L	Liver/CNS possible carcinogen	0.01 mg/L	Airplane glue

Table 3 Chemicals leached from polyethylene, HDPE, PEX

Chemical leached	CAS No.	Source or primary use if additive	Allowable limit or risk factor	Potential health effects	Odor (or taste) threshold	Odor (or taste)
Bisphenol A	80-05-7	Fungicide	Oral RfD 0.05 mg/kg/day	Endocrine disruptor		Medicinal

Table 4 Chemicals Leached from PVC or CPVC

Chemical leached	CAS No.	Source or primary use if additive	Allowable limit or risk factor	Potential health effects	Odor (or taste) threshold	Odor (or taste)
Antimony	7440-36-0	Accidental contaminant	MCL 6 μg/L	Blood, decreased longevity		Metallic
m-Chlorophenol	108-43-0		(no MCL)	CNS, kidney, liver	5 μg/L	Phenolic
Cyclohexanone	108-94-1		(no MCL)	Possible carcinogen (IARC 3)	0.12 mg/L	Similar to acetone

Table 5 Chemicals leached from Nitrile-Butadiene Rubber (NBR)

Chemical leached	CAS No.	Source or primary use if additive	Allowable limit or risk factor	Potential health effects	Odor (or taste) threshold	Odor (or taste)
2,4,5-Trichlorophenol	95-95-4	Fungicide, bactericide	Oral RfD 0.1 mg/kg/day	Liver, kidney	1 ppm? (based on 2,4,6-TCP)	Medicinal, strong

Table 6 Chemicals Leached from Styrene-Butadiene Rubber (SBR)

Chemical leached	CAS No.	Source or primary use if additive	Allowable limit or risk factor	Potential health effects	Odor (or taste) threshold	Odor (or taste)
2,4,5-Trichlorophenol	95-95-4	Fungicide, bactericide	Oral RfD 0.1 mg/kg/day	Liver, kidney	1 ppm? (based on 2,4,6-TCP)	Medicinal, strong
Styrene	100-42-5		MCL 0.1 mg/L	Liver/CNS possible carcinogen	0.01 mg/L	Airplane glue

Table 7 Chemicals associated with solder

Chemical leached	CAS No.	Source or primary use if additive	Allowable limit or risk factor	Potential health effects	Odor (or taste) threshold	Odor (or taste)
Copper	7440-50-8		Action limit 1.3 mg/L	GI, liver, kidney	5 ppm	Metallic
Antimony	7440-36-0	Accidental contaminant	MCL 6 μg/L	Blood effects, decreased longevity		Metallic

Note: while these descriptors have been independently traced to specific chemicals, the descriptors can easily overlap, but are more distinctive from other descriptors like plastic.

Chemical(s): styrene, xylenes, alkyl benzenes, acetone, tetrahydrofuran, methyl ethyl ketone, cyclohexanone, methylpyrolidone, cycloheptane, 2-methylcyclopentanone; methyl *t*-butyl ether not from materials leaching but a gasoline additive. Check source water for contamination and/or PVC and polyethylene pipes for permeation of contaminated soil and/or gasoline (leaking underground storage tanks)

Sources/materials: polyester resin in water tanks, polyethylene pipes, PVC pipes, epoxy coatings, gaskets (descriptor may be more like "hydrocarbon"), primers, cement liners, solvents

(b) Subdescriptor – kerosene, gasoline; rubber gaskets for ductile iron pipes

(c) Subdescriptor – plastic

Chemicals: methyl methacrylate, BHT

Sources/materials: PVC pipe, polyethylene pipe (HDPE)

(d) Subdescriptor – burnt plastic

Chemicals: 4-Methyl-2,6-di-*t*-butylphenol, oxidized BHT

Sources/materials: PVC pipes, polyethylene pipe (HDPE)

3. Odor Wheel Category: fruity/sweet/flowery/fragrant/vegetable

Subdescriptor – vanilla

Sources/materials: degradation product of lignosulfonates, cement/concrete pipes and liners

4. Fishy/rancid

Subdescriptor – rancid

Sources/materials: lubricants used for ductile iron pipes (soapy/rancid)

Table 8 Possible sources of taste-and-odor events by categories on the Taste-and-Odor Wheel

Major category	Candidate materials
Earthy/musty/moldy Also: mushroom, beets, wet/damp basement, potato bin, cork etc.	Halogenated anisoles; phenols biotransformed by fungi in distribution system. Note: first rule out contribution from natural sources like geosmin and MIB (from cyanobacteria)
Chlorinous/ozonous	May be the product of the reaction of disinfectant with the material (if not the disinfectant itself; or a typical halophenol)
Marshy/swampy/septic/ sulfurous Includes "rubbery"	Primarily rubber: from cement mortar lining, rubber gaskets and o-rings; synthetic rubber covers on storage facilities; rubber coatings and sealants, etc. (If not from decaying vegetation or septic conditions)
Fragrant/vegetable/fruity/ lowery May include "sweet"	If "sweet", see also Chemical/Hydrocarbon and Medicinal/Phenolic categories. Fruity: silicone from sealants and lubricants. Fruity/citrus: highly oxidized chemicals (oxidation from oxygen in water, or from disinfection) from lubricants or cement mortar lining
Fishy/rancid	Fishy: diethanolamine (emulsifier, dispersing agent) from pipes/liners, cement/concrete. Rancid: oxidized chemicals (from chlorination or oxygen or ozonation) from lubricants or cement mortar linings
Medicinal/phenolic	Primers and cements, acrylic coatings, rubber, gaskets and o-rings, pipes and liners
Chemical/hydrocarbon/misc.	Rubber gaskets; pipes: PVC, HDPE; BHT
Mouth feel/nose feel Metallic, astringent, drying, tingling, chalky, oily, pungent	Metals: metallic materials (pipes, solder, possibly cementious materials). Chalky – calcium carbonate in cementious materials

Conclusion

In this paper, lists of potential chemical contaminants are identified for system components typical of most drinking water distribution systems. Characteristics of these are provided where available. In addition, the use of sensory analysis provides taste-and-odor descriptors which can be matched with Taste-and-Odor Wheel descriptors to identify potential system materials causing undesirable taste-and-odor characteristics in drinking water.

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